Dynamic Load Sharing in Heavy Vehicle Suspensions

Further Analysis of the Equalisation Effects of Larger Air Lines

Lloyd Davis[1] and Jonathan Bunker[2]

[1]ERDS Pty Ltd, [1,2]Science and Engineering Faculty, Queensland University of Technology
Queensland University of Technology,

[1]PO Box 578 Morningside Qld, Australia 4170, [2]GPO Box 2434, Brisbane 4001, Australia

[1]admin@erds.com.au; [2]j.bunker@qut.edu.au.

***Abstract*- This paper provides details on comparative testing of axle-to-chassis forces of two heavy vehicles (HVs) based on an experimental programme carried out in 2007. Dynamic forces at the air springs were measured against speed and roughness values for the test roads used. One goal of that programme was to determine whether dynamic axle-to-chassis forces could be reduced by using larger-than-standard diameter longitudinal air lines. This paper presents a portion of the methodology, analysis and results from that programme. Two analytical techniques and their results are presented. The first uses correlation coefficients of the forces between air springs and the second is a Student's t-test. These were used to determine the causality surrounding improved dynamic load sharing between heavy vehicle air springs with larger air lines installed longitudinally compared with the standard sized air lines installed on the majority of air-sprung heavy vehicles.**

Keywords-Heavy Vehicle; Suspension; Dynamic Load Sharing; Load Sharing; Load Sharing Measurement; Dynamic Load Equalisation.

I. INTRODUCTION

An experimental programme in 2007 measured heavy vehicle (HV) forces when they were travelling over typical urban roads. One goal of that programme was to measure dynamic axle-to-chassis forces to determine if dynamic load sharing in HV suspensions could be improved by using larger-than-standard diameter air lines longitudinally on HV air suspensions. Clearly, the programme could not determine this generically but two HVs were outfitted with larger longitudinal air lines; the 'Haire suspension system' as a proof-of-concept. The 'Haire suspension system' is a proprietary suspension system which connects HV air springs longitudinally using larger-than-standard air lines. The transverse air line remains as standard for this system. The 'Haire suspension system' is shown schematically; LHS in Fig. 1. The larger longitudinal air lines installed for the test programme were used as the test case. Standard-sized air lines were the control case.

This paper presents methodology, analysis and results derived from axle-to-chassis forces for standard-sized longitudinal air lines vs. the test case where larger longitudinal air lines were fitted. Measures such as the correlation coefficient and the dynamic load sharing coefficient (DLSC) are derived from the axle-to-chassis forces and discussed. Noting where these measures are altered due to the fitment of larger longitudinal air lines leads to conclusions regarding the possibility that dynamic load sharing in HV suspension may be improved by fitting larger longitudinal air lines to air-suspended HVs.

II. BACKGROUND

A. Methodology and metrics

1) Experimental procedure

Included in a larger test programme [1], two heavy vehicles (HVs) were used for dynamic load sharing testing. They were a triaxle semi-trailer towed by a prime mover and an interstate coach with a drive axle and a tag axle as the rear axle group. The triaxle group of the semi-trailer and the drive and tag axle group of the coach were instrumented with air pressure transducers on their respective air springs. The air springs (air bags) of the axle group of interest were configured such that they could be connected using either standard longitudinal air lines or larger-than-standard longitudinal air lines as shown in Fig. 1.

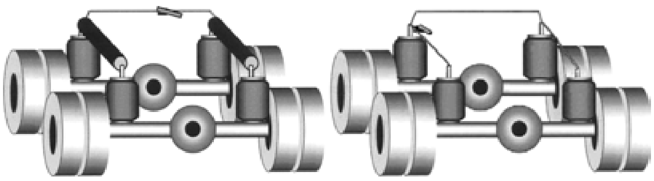

Fig. 1 Schematic layout of a suspension with larger longitudinal air lines (left) in contrast with standard air lines (right)

Test masses were used to load the axles of interest to their maximum legal load. Fig. 2 shows a detail of the large longitudinal air line installation (enlarged air line 'A') entering an air spring (arrow).

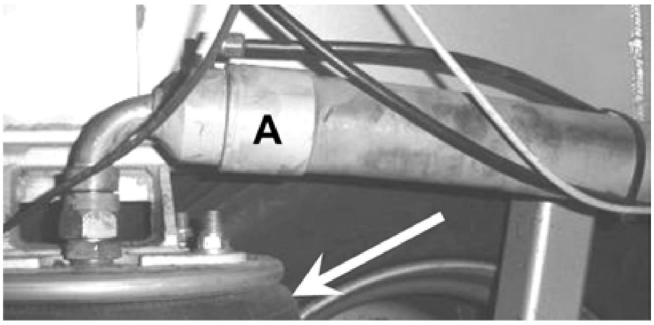

Fig. 2 Large longitudinal air line (A). Typical for each air spring (arrow) on axle/s of interest

Air pressure transducers (APTs) were connected to the air lines supplying the air springs on each axle group of interest. The APTs allowed measurement of body-to-chassis signals at each air spring. Accelerometers were installed on the axles of interest as close as possible to the wheel hubs. This was to measure the acceleration of the wheels during the tests. A customised TRAMANCO P/L CHEK-WAY® telematics system was used to record the dynamic signals from the APT and accelerometer outputs with a sampling rate of 1000 Hz.

The tests comprised driving the HVs over a series of typical urban road sections at speeds ranging from 40 km/h to 90 km/h. Ten seconds of dynamic signal data from the APTs and the accelerometers were recorded per road section. This resulted in data in the form of a time-series signal from each air spring and each accelerometer on each axle of interest on each test HV for the two cases of air line size at the various test speeds. The sections of road varied from smooth with long undulations to rough with short undulations.

1) Dynamic load sharing – correlation metric

Dynamic load sharing in a HV axle group should be detectable by finding the cross-correlation of forces between any two corresponding air springs in that group. Were dynamic load sharing occurring between air springs, any force on one air spring should result in a force being transferred to another air spring during this process. Detecting the degree of correlation between those pairs of forces should indicate the extent of dynamic load sharing; the higher the correlation, the greater the amount of dynamic load sharing occurring between the two air springs concerned.

This project used standard air lines for the control case and larger longitudinal air lines as the test case. It needs to be emphasised here that a HV in motion is a dynamic system with a number of modes. The axle modes will be correlated without dynamic load sharing (because they experience the same excitation force from the road) but there will be a phase lag. The analysis presented herein was performed on the data gathered during this experimental programme by considering only instantaneous load sharing by considering only the instantly contemporaneous signals between each pair of air springs (see Fig 3 later). Accordingly, since dynamic load sharing was analysed by comparing the instantaneous signals from each pair of air springs, this phase lag was eliminated from the analysis.

That the body modes of bounce, roll and pitch were present is a given. To neutralise their effects when comparing the two cases under test, the testing procedure used the same portions of road, the same test loads on the same HV travelling at the same speeds for each pair of tests. The only variable changed from one test run to the next for the tested parameters for any pair of test runs was the size of the air lines between air springs within the axle group of interest. Manual examination of each 10 second signal ensured that only those portions of matched pairs of signals were used for this analysis.

Analysis determined the correlation coefficient between pairs of wheels or air springs on the same sides of the semi-trailer and the coach in real time. This was undertaken for the datasets recorded from each air spring and derived for each wheel as detailed. The closer the correlation coefficient was to 1.0, the greater the statistical significance between the elements compared (*i.e.* between air springs). Alterations consisted of changing the size of the longitudinal air lines along each side of the vehicles. The size of the transverse air lines from one side to the other on the tested HVs was not altered. Accordingly, only pairs of air springs on the same side of the coach and the semi-trailer were investigated for changes to dynamic load sharing.

2) Road Roughness

Road roughness is usually designated by a standard measure, the international roughness index (IRI), found using calibrated vehicles. The units of this roughness measure are mm/m or m/km. IRI indicates an amount of vertical movement relative to travelled horizontal distance. This roughness measure is standardised [2].

Each hub on each axle of interest had acceleration data recorded during the on-road testing [1]. A double integration was performed on the vertical acceleration data at a representative axle of each test HV. Net vertical acceleration measured at the hub was used after the constant gravity component was removed. This yielded a “novel roughness” value of positive vertical movement of the axle for a given horizontal distance travelled. The horizontal distance travelled for each 10 s of recorded data was different for each test speed. Accordingly, the velocity of each HV during each test needed to be included in the derivation of the roughness results.

Eq. 1 provides a mathematical derivation of the “novel roughness” value used.

$$\text{“novel roughness”} = \frac{\left[\int_0^n \int_{a=0}^{a=\infty} a\right]}{v} \text{ m/m} \qquad \text{Eq. 1}$$

where:

a = net upward hub acceleration during the recording period;

v = velocity in metres *per* 10 s and

n = the number of data points recorded over 10 s.

nota bene: only the positive values of a were integrated, in line with the philosophy that the IRI measure is determined as a positive slope.

The units in Eq. 1 were resolved as follows:

a: metre.s^{-2}

a integrated twice:

$$\iint \text{metre.s}^{-2} \Rightarrow \text{metres} \qquad \text{Eq. 2}$$

v: horizontal metres/10 s.

Eq. 2 provided the transformation of measured acceleration into the positive vertical displacement (in metres) that the hubs moved during the 10 s recording period (vertical metres/10 s) *per* test run. Returning to Eq. 1, the units of "novel roughness" may then be resolved:

$$\text{"novel roughness" units} = \frac{f[a]}{v} = \frac{\text{vertical metres/10 s}}{\text{horizontal metres/10s}} = \frac{\text{vertical metres}}{\text{horizontal metres}}$$

A factor of 1000 was applied to render this "novel roughness" value into mm/m. This "novel roughness" value or "novel roughness" measure should not be equated to the IRI value of the roads used for the testing. It was derived to provide an *indicative measure* of roughness as experienced by each test HV axle at a representative hub accelerometer. The tyres, axle mass and wheel mass varied with each test vehicle. The "novel roughness" value was derived from acceleration signals measured at the wheels and was unique to each vehicle. . In this way, it was similar to the methodology for determining IRI [2]. Even so, the "novel roughness" value provided an independent variable against which to plot air spring force as the dependant variable.

3) Dynamic Load Sharing Coefficient

Dynamic load sharing coefficient (DLSC) was applied to the air spring data for the coach and the semi-trailer for the two cases of larger longitudinal air lines [3]. Individual results for each pair of air springs *on that side of the HV* were derived. This technique altered the application of the DLSC to one that derived the DLSC for each air spring using the forces measured at all of the air springs on the same side as that particular air spring:

$$DLSC_i = \sqrt{\frac{\sum (DLS_i - \overline{DLS_i})^2}{k}} \qquad \text{Eq. 3}$$

where:

Dynamic load sharing (DLS) at air spring i

$$= DLS_i = \frac{nF_i}{\sum_{i=1}^{i=n} F_i} \qquad \text{Eq. 4}$$

n = number of air springs on the side of air spring i;

F_i = instantaneous force at air spring i; and

k = number of instantaneous values of DLS, *i.e.* number of terms in the dataset [3].

III. Results

Suspension metrics of correlation and DLSC were derived from the data gathered during the road tests described above for the test case of larger longitudinal air lines *vs.* standard air lines. Some results from this approach, using test speed as the independent variable against which to plot the suspension metrics for the test case and the control case, have been published elsewhere [4] [5] [6]. An alternative approach to presenting derived suspension metrics for the case of standard air lines as the control case and larger longitudinal air lines as the test case is shown in the following section. Note that front-to-back dynamic load sharing alterations arising from the use of larger longitudinal air lines were the focus since transverse air line sizes had not been altered.

A. Alterations to DLSC from larger longitudinal air lines - correlation method

Datasets of air spring forces derived from the road tests [1] for the multi-axle groups of interest were analysed by comparing correlation coefficients for the control case of standard longitudinal air lines *vs.* the test case of larger longitudinal air lines. This comparison applied to pairs of air springs from each side of the coach (top, Fig.3) and the semi-trailer (bottom, Fig 3) in real time.

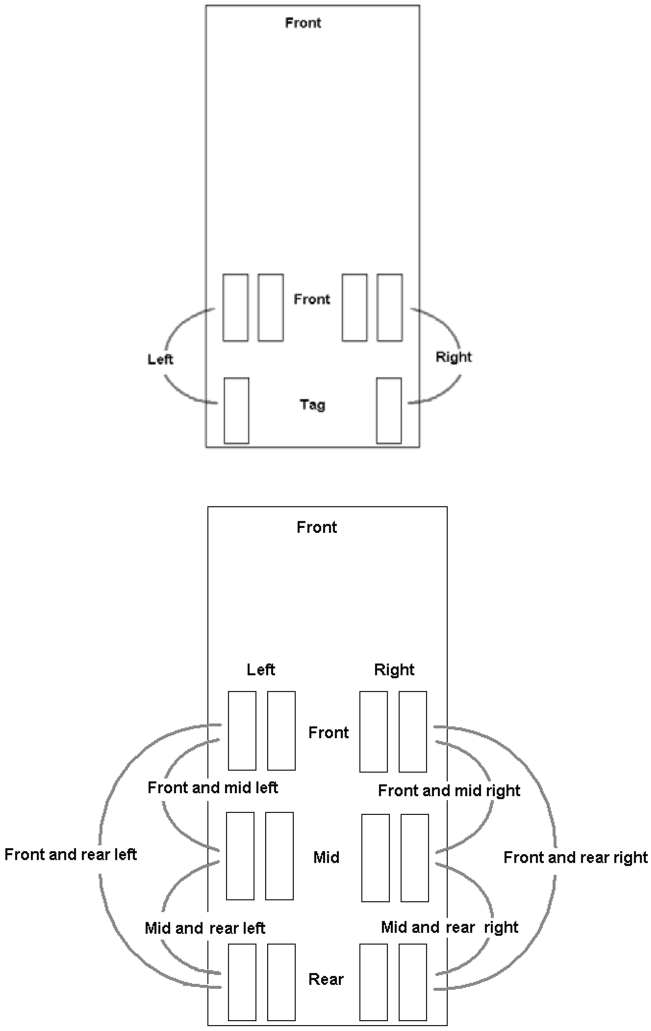

Fig 3 Illustrating the pairs of air springs (and their associated wheels) tested for load sharing using correlation. Top, coach; bottom, semi-trailer.

To reduce the amount of data displayed to a tractable level, representative and indicative samples from each test speed's correlation coefficients for each front-to-back pair of air springs and wheels (Fig 3) were plotted for the test case and the control case. The distribution of the correlation coefficients within the variable-space was then bounded to indicate their maxima and minima for the test case and the control case. The results are shown in Figs. 4 and 5.

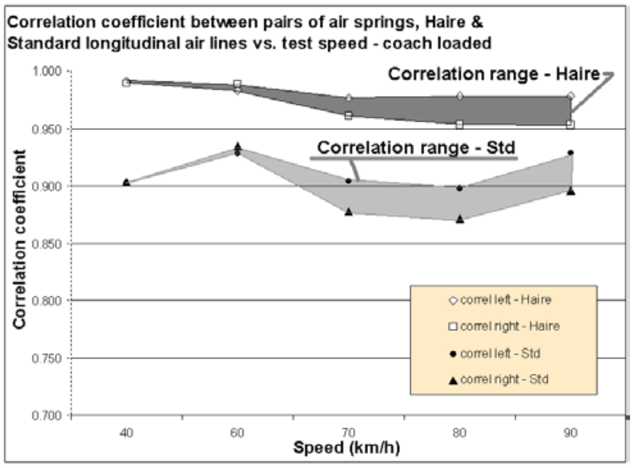

Fig 4 Correlation coefficient distribution of air spring forces for larger (Haire) longitudinal air lines and standard air lines *vs.* test speed – coach.

Fig. 4 suggested strongly that the larger longitudinal air lines altered the dynamic load sharing at the air springs by a statistically significant amount. The distribution bounded by the correlation coefficients for the case of larger longitudinal air lines occupied a different variable-space from that for the control case of standard air lines.

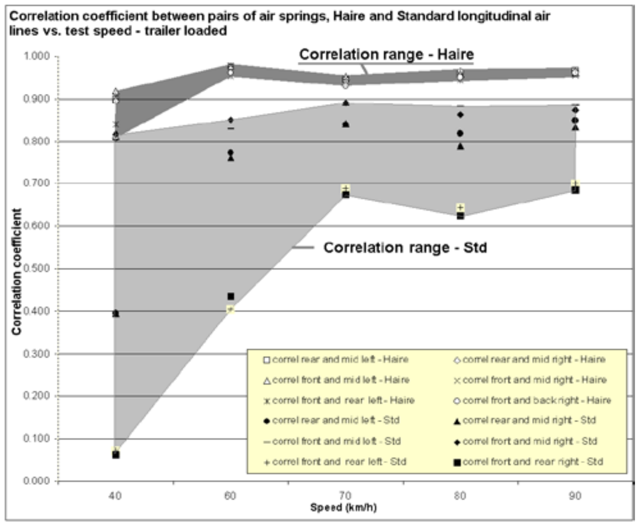

Fig. 5. Correlation coefficient distribution of air spring forces for larger (Haire) longitudinal air lines and standard air lines *vs.* test speed – semi-trailer.

Fig. 5 likewise showed a clear differentiation between the distributions of correlation coefficients for the two cases tested. It was indicative of a situation where larger longitudinal air lines made a statistically significant difference to dynamic load sharing at the air springs. These results for dynamic load sharing at the air springs of the coach and the semi-trailer will be discussed in detail later.

B. Alterations to DLSC from larger longitudinal air lines - t-test

The values given by [2] in developing the IRI were used as a guide to develop a set of independent variables based on three bands of "novel roughness" values. The bands, in "novel roughness" units of mm/m, were chosen as:

below 3;

from 3 to 4; and

above 4.

These choices within the total range of the "novel roughness" values provided approximately equal numbers of tests within each band. It is emphasised that the "novel roughness" value was derived for each tested HV and was not related to the IRI developed by [2].

A t-test for variations in metrics for the two cases within each "novel roughness" band was performed for the air spring data. A heteroscedastic test option was chosen since the datasets had unequal variances [7] within each band of "novel roughness". A conservative value for $\alpha = 0.1$ was chosen since road-damage business cases generally use this α value as an upper bound. A one-tailed test [8] was chosen since previous work [9] indicated that the larger longitudinal air lines altered some dynamic measures in a particular direction. A two-tailed test was considered but discarded since its other tail would have informed the case for performance improvement beyond the confidence limit [10].

The DLSC for the coach rear group air springs was derived using the air spring data for that side, for the two sizes of longitudinal air lines. The t-test results of these DLSC values for those air springs for the control case *vs.* the test case are shown in Table 1. The results of deriving the DLSC for the coach indicated beneficial alterations to dynamic load sharing between the air springs along each side when they were connected with larger longitudinal air lines.

Where the results of the t-test indicated that there was a 90 percent or greater probability (*i.e.* a result less than or equal to 0.1) that the population means of the two cases varied due to the experimental difference and not error, these occurrences are shown in shaded cells below. Where the t-test indicated this statistical significance, the percentage change between the averaged derived parameter values within each "novel roughness" band population for the two cases is shown parenthetically.

TABLE 1 T-TEST TABLE AND PERCENT ALTERATIONS TO DYNAMIC LOAD SHARING COEFFICIENT (DLSC) FOR THE COACH AIR SPRINGS AGAINST "NOVEL ROUGHNESS" BANDS.

"Novel roughness" (mm/m)	t-test results for alterations to coach rear group air spring force dynamic load sharing coefficient, and, where significant, (percent change)			
	Tag left	**Tag right**	**Drive left**	**Drive right**
< 3	0.00229 (62.9)	0.000771 (55.5)	0.00356 (52.6)	0.00121 (48.0)
3 to 4	0.000235 (64.1)	0.00664 (58.3)	0.000185 (58.0)	0.00733 (54.8)
> 4	0.0393 (43.2)	0.0629 (40.5)	0.0982 (31.4)	0.0882 (34.8)

The values shown in Table 1 aligned with the results shown in Fig. 4, albeit for a different independent variable. The results in Table 1 indicated that dynamic load sharing was occurring at the air springs to a greater degree with the larger longitudinal air lines than for the case of standard air lines. An improvement of approximately 30% to 60% was evident for the case of larger longitudinal air lines.

TABLE 2 T-TEST TABLE AND PERCENT ALTERATIONS TO DYNAMIC LOAD SHARING COEFFICIENT FOR THE SEMI-TRAILER AIR SPRINGS AGAINST "NOVEL ROUGHNESS" BANDS.

Novel rough -ness (mm/ m)	t-test results for alterations to semi-trailer air spring force dynamic load sharing coefficient, and, where significant, (percent change)					
	Rear left	**Rear right**	**Mid left**	**Mid right**	**Front left**	**Front right**
< 3	0.0034 (78.4)	0.0021 (79.7)	0.0012 (60.2)	0.000060 (61.9)	0.0031 (75.6)	0.0025 (76.1)
3 to 4	0.024 (76.1)	0.043 (77.0)	0.0033 (59.2)	0.041 (58.1)	0.027 (73.9)	0.047 (74.9)
> 4	0.033 (66.2)	0.031 (69.7)	0.0123 (45.5)	0.022 (50.8)	0.040 (62.2)	0.041 (64.6)

Individual DLSC values *per* semi-trailer air spring were derived from the air spring data for that side and are shown in Table 2. These data, supported by the distinct difference in the two areas of variable-space in Fig. 5, indicated that dynamic load sharing at the air springs was improved by approximately 45% to 80% with the larger longitudinal air lines connecting fore-and-aft air springs compared with standard longitudinal air lines on the semi-trailer. This result was of a similar order of magnitude to that shown for the coach in Table 1.

IV. DISCUSSION

Dynamic load sharing using correlated air spring force data was plotted against the independent variable of test speed. This process indicated strongly that there was an increase in dynamic load sharing for the test case of larger longitudinal air lines at the axle-to-chassis interface for the multi-axle HVs tested (Figs. 4 and 5). These results were for an indicative range of correlations and indicative test speeds and showed, for both heavy vehicles tested, that the range of correlation coefficients was separate and distinct for the two cases of air line size. The strong indicators from the correlation coefficient approach required a different methodology to determine if it were valid.

The dynamic load sharing coefficient (DLSC) was applied to the same air spring data but determined against a different independent variable in the form of a range of "novel roughness" measure bands to separate causality even further. This was to determine alterations to air spring DLSC along either side of the coach and the semi-trailer for the two cases of air line size. The t-test results for the DLSC alterations *per* air spring *per* side showed consistent improvement across all "novel roughness" bands.

It was noticeable that dynamic load sharing, derived from the DLSC, improved across the board for the coach and the trailer in the order of 30% to 80% for the test case of larger longitudinal air lines *vs.* standard air lines, depending on vehicle and roughness.

V. CONCLUSION

Two dynamic load sharing suspension metrics, the DLSC and the correlation coefficient between pairs of air springs, were derived for the two heavy vehicles tested. These were shown to alter for the test case of larger longitudinal air lines by a statistically significant degree leading to the conclusion that dynamic load sharing was facilitated by larger air lines.

Approximate improvements from 30% to 80% in dynamic load sharing occurred with the larger longitudinal air lines. These figures indicate that further research needs to be undertaken to determine whether this improvement in dynamic load sharing has the potential for concomitant reductions in shock loadings and reduced damage to cargo, potentially smaller suspension forces and therefore lighter suspension components. Any gains in these areas should result in more payload per vehicle without overall mass increases, fewer trips for a given freight task and increased life expectancy of suspensions, chassis components and on-board systems. Accordingly, concomitant reductions in HV trip numbers would benefit operators and the public.

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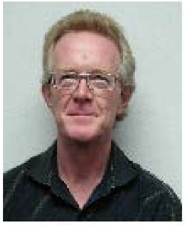

Lloyd E. Davis has a Bachelor of Engineering from the Queensland Institute of Technology (1983). He has a Graduate Diploma (Control) from the Queensland Institute of Technology (1985) and a PhD in heavy vehicle dynamics from the Queensland University of Technology (2010).

From 2002 to 2007, he was a full-time member of the implementation team for the Intelligent Access Program (IAP) – the national project to monitor heavy vehicles using GPS technology. In 2007, he was seconded part-time to the IAP Stage 2 project to determine on-board mass accuracy of HV measurement systems and to develop tamper-evident algorithms for them; a part time commitment he maintained until leaving Transport and Main Roads in September 2012. His current position is as a design engineer for ERDS in Brisbane, Australia. He maintains his interests as a QUT alumnus, in research into heavy vehicle dynamics, vehicle telematics, co-operative ITS and related fields.

Dr. Davis is a Fellow of the Institution of Engineering and Technology. His joint paper, L. Davis, S. Kel and R. Sack, *Further development of in-service suspension testing for heavy vehicles*, Australasian Transport Research Forum, 30th, Melbourne, 2007, was awarded the John H Taplin Prize for the best scientific ATRF paper and presentation that year.

Jonathan M. Bunker has Bachelor of Engineering (Civil) with Honours 1 (1991) and a Doctor of Philosophy (1996), both from the Queensland University of Technology. He is an Associate Professor in Civil Engineering, Science and Engineering Faculty, Queensland University of Technology

He researches and lectures in traffic engineering, transport planning, highway engineering, infrastructure asset management, freight logistics and sustainable development practices. Prior to joining the faculty at QUT he practiced as a consulting transport engineer in Australia and the United States of America.

Dr. Bunker is a past President of the Australian Institute of Traffic Planning and Management, is a Fellow of the AITPM and Member of the Institution of Engineers Australia.